METHOD OF CONTROLLING THE FUEL INJECTION PRESSURE OF AN INTERNAL COMBUSTION ENGINE COMMON RAIL INJECTION SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a method of controlling the fuel injection pressure of an internal combustion engine common rail injection system.

The present invention may be used to particular advantage, though not exclusively, in automotive applications, to which the following description refers purely by way of example.

The present invention, in fact, may also be used in so-called "no-road", *i.e.*, non-automotive, applications to control internal combustion engines of pumps, welders, generators, etc., and more generally in any industrial application requiring the generation of mechanical power.

Description of the Related Art

As is known, the common rail injection systems currently installed on vehicles comprise a number of injectors for drawing high-pressure fuel, under the control of an electronic control unit, from a common rail, and injecting it into respective cylinders.

The common rail is supplied with fuel by a high-pressure mechanical, normally piston, pump, in turn supplied with fuel from the vehicle tank by a low-pressure pump. The pressure of the fuel in the common rail is controlled by a pressure regulator, which drains any surplus fuel, pumped in excess of requirements, from the common rail to keep the common rail at a given pressure, during injection, depending on the power required.

The pressure regulator normally comprises a solenoid valve, *i.e.*, a valve controlled by an electromagnet, which, when closed, allows supply to the

common rail of all the fuel pumped by the high-pressure pump, and, when partly or fully open, drains the surplus fuel from the common rail along a drain conduit into the tank.

More specifically, the solenoid valve comprises a shutter, which is kept closed by a spring when the electromagnet is deenergized, and which is kept open when the electromagnet is energized. More specifically, the electromagnet is driven by the electronic control unit by means of a control signal, the duty cycle of which determines the extent to which the electromagnet is energized, and therefore the extent to which the shutter is opened.

Since, in common rail injection systems currently installed on vehicles, the high-pressure pump is a continuous-delivery pump not timed with the engine, *i.e.*, a pump activated, for example, by a cam, to supply fuel substantially continuously to the common rail, whereas the injectors are activated at a given stroke in the engine cylinder cycle, the high-pressure pump must be designed to ensure maximum fuel draw by the injectors as a whole during the engine cycle.

European Patent Application 01130851.7 – filed by the present Applicant on 27.12.2001, published on 03.07.2002 under number EP-1219827, and claiming priority over Italian Patent Application TO2000A01228 of 29.12.2000 – recently proposed a special common rail injection system configuration which can also be fitted to old-type diesel engines, in which, as is known, the injectors are supplied directly by a high-pressure pump whose delivery is discontinuous, timed with the engine, and cyclically constant, *i.e.*, a pump operated synchronously, *i.e.*, pumping in time with the injectors.

More specifically, the above patent application describes a high-pressure pump comprising one or more pumping elements, each having a cylinder and a piston, which is activated by a corresponding cam to pump in time with the relative injector to appropriately control fuel pressure variations in the common rail. The cams are rotated by the engine, and more specifically are carried by a pump drive shaft preferably defined by an engine shaft performing other functions, such

as the shaft operating the cylinder intake and exhaust valves, or the drive shaft itself.

In the case of a high-pressure pump with one pumping element, the piston is controlled by a cam shaped to produce a number of axial movements of the piston inside the cylinder, and so produce a number of fuel deliveries to the common rail at each engine cycle.

In some applications, the high-pressure pump piston is controlled by an asymmetrical cam, *i.e.*, a cam shaped to produce a number of different axial movements of the piston inside the cylinder.

Figure 1 shows an example of the movement of the high-pressure pump piston at each engine cycle as a function of the asymmetrical cam profile. More specifically, Figure 1 relates to fuel supply to a two-cylinder engine by a high-pressure pump with one pumping element, and wherein two fuel injections, one per cylinder, are made at each engine cycle.

It should be pointed out that further injections per cylinder can be made by drawing directly from the fuel in the rail, which remains pressurized even in the absence of delivery.

As can be seen, during the engine cycle, the cam produces a first and a second axial movement of the piston inside the cylinder, to produce a first and a second fuel delivery to the common rail, so that the fuel in the rail is brought to a given required pressure value P_R at the instants in which fuel is injected into the first and second cylinder respectively.

As shown in Figure 1, a drawback of common rail injection systems of the above type lies in the fuel pressure in the common rail during the second delivery reaching, at the instant of synchronism, a different (typically higher) value with respect to the required pressure value P_R due to dispersion.

The amount of fuel, in fact, in the high-pressure pump at the start of the second delivery is less than at the start of the first delivery, and the geometric effect of the reduction in volume inside the cylinder, as the piston advances along

the cylinder, produces a greater increase in pressure at the second delivery, on account of the elastic fuel volumes on which compression is exerted being smaller than at the start of the first delivery.

This difference in fuel pressure in the common rail during deliveries after the first has various negative effects on both consumption and engine emissions.

BRIEF SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method of controlling the fuel injection pressure of an internal combustion engine common rail injection system, designed to eliminate the aforementioned drawbacks.

According to the present invention, there is provided a method of controlling the fuel injection pressure of an internal combustion engine common rail injection system, as claimed in Claim 1.

BRIEF DESCRIPTION OF THE DRAWINGS

A non-limiting embodiment of the present invention will be described by way of example with reference to the accompanying drawings, in which:

Figure 1 shows, schematically, the piston movement of a common rail injection system high-pressure pump;

Figure 2 shows, schematically, a system for controlling the fuel injection pressure of an internal combustion engine common rail injection system in accordance with the teachings of the present invention;

Figure 3 shows a block diagram illustrating the operations performed by an electronic control unit for controlling the fuel injection pressure of an internal combustion engine common rail injection system.

DETAILED DESCRIPTION OF THE INVENTION

Number 1 in Figure 2 indicates as a whole a system for controlling the fuel injection pressure of an internal combustion engine common rail injection system 2.

For the sake of simplicity, the following description refers to a two-cylinder engine, though what is stated also applies to engines with any number of cylinders timed with one another.

Injection system 2 comprises a first and a second injector 3 for drawing high-pressure fuel, under the control of an electronic control unit 4, from a common rail 5, and injecting it into respective cylinders.

Injection system 2 also comprises a mechanical high-pressure pump 6, which is supplied with low-pressure fuel from the tank by a low-pressure pump (not shown), and supplies high pressure fuel to common rail 5 along a delivery conduit 7 fitted with a one-way valve 8 preferably, though not necessarily, integrated in pump 6.

Injection system 2 also comprises a pressure regulator 9 connected to common rail 5, and which drains any surplus fuel, pumped in excess of requirements, from the common rail to keep the common rail at a given pressure, during injection, depending on the power required.

Pressure regulator 9 comprises a solenoid valve 10, *i.e.*, a valve controlled by an electromagnet, which, when closed, allows supply to common rail 5 of all the fuel pumped by high-pressure pump 6, and, when partly or fully open, drains the surplus fuel from common rail 5.

More specifically, solenoid valve 10 comprises a shutter 11, which is kept closed by a spring 12 when the electromagnet is deenergized, and which, when the electromagnet is energized, is kept open by a force equal to the difference between the preload force of the spring and the contrasting force produced by a control signal S_{COM} generated by electronic control unit 4.. More specifically, the electromagnet is driven by electronic control unit 4 by means of

power control signal S_{COM}, the duty cycle DC of which determines the extent to which the electromagnet is energized, and therefore the resulting preload of shutter 11.

High-pressure pump 6 is a discontinuous pump operated synchronously, *i.e.*, pumping in time with each injector 3, so as to deliver fuel during injection by each injector, to minimize fuel pressure variations in common rail 5 and prevent pressure collapsing as a result of injection.

In the example shown, high-pressure pump 6 has one pumping element, *i.e.*, comprises a cylinder 13, and a piston 14 mounted to slide axially inside cylinder 13 to produce a number of fuel deliveries to common rail 5 at each engine cycle.

Piston 14 is operated by an asymmetrical cam (not shown) rotated by the engine and shaped to produce a number of axial movements of piston 14 inside cylinder 13, and a first and at least a second fuel delivery to common rail 5 at each engine cycle.

With reference to Figures 2 and 3, the electronic control unit operates on the basis of engine parameters measured on the engine by appropriate sensors (not shown), and on the basis of operating parameters of injection system 2, to supply control signal S_{COM}, the duty cycle DC of which determines the equivalent preload of pressure regulator 9 and so regulates the pressure in common rail 5.

More specifically, for each engine cycle and as described in detail later on, electronic control unit 4 determines the duty cycle DC of control signal S_{COM} synchronously with each fuel delivery by high-pressure pump 6 and as a function of the following parameters: engine speed N; engine load L; the required pressure P_R in common rail 5 during each delivery, which depends on the power required of the engine; the actual pressure P_E in common rail 5 during each delivery; and the fuel pressure difference D_P in common rail 5 between the first and second fuel delivery by high-pressure pump 6.

In the example shown, pressure difference D_P is defined by the difference between the final fuel pressure value in common rail 5 during the second delivery, and the final fuel pressure value in common rail 5 during the first delivery.

With reference to Figure 3, electronic control unit 4 – of which only the parts required for a clear understanding of the present invention are shown – comprises a correction block 15, which receives the so-called engine point defined by engine speed N and engine load L, and supplies a total correction coefficient C_{CR}.

Electronic control unit 4 also comprises a control block 16, which receives the required pressure P_R and actual pressure P_E in common rail 5, and total correction coefficient C_{CR}, and supplies control signal S_{COM} for controlling pressure regulator 9.

More specifically, the control signal S_{COM} supplied by control block 16 has a duty cycle DC which, during the first delivery by high-pressure pump 6, is calculated as a function of the difference between the required pressure P_R and actual pressure P_E in common rail 5 to bring the actual pressure P_E to the same value as the required pressure P_R, and which, during the second delivery by high-pressure pump 6, is corrected as a function of total correction coefficient C_{CR} supplied by correction block 15, so as to adjust the actual pressure P_E generated during the second delivery in common rail 5 to the required pressure P_R value, and so eliminate the pressure difference D_P between the first and second delivery.

With reference to Figure 3, correction block 15 substantially comprises a static correction block 17, which receives engine speed N and engine load L, and supplies a static correction coefficient C_{CL}; and an adaptive correction block 18, which receives engine speed N, engine load L, and an adaptive update coefficient C_{AG} explained in detail later on, and supplies an adaptive correction coefficient C_{AD}.

Correction block 15 also comprises an adding block 19, which receives adaptive correction coefficient C_{AD} and static correction coefficient C_{CL}, and supplies total correction coefficient C_{CR}, *i.e.*, $C_{CR}=C_{AD}+C_{CL}$.

More specifically, static correction block 17 stores an electronic static correction map containing a static correction coefficient C_{CL} for each engine point defined by a respective pair of engine speed N and load L values.

More specifically, the electronic static correction map is defined by a two-dimensional matrix, each box of which is identifiable by a respective pair of engine speed N and load L values, and contains a respective static correction coefficient C_{CL} value determined experimentally at an initial calibration stage of the injection system.

In the example shown, the static correction coefficient C_{CL} value indicates the nominal correction, as a percentage value, to be made to duty cycle DC of control signal S_{COM} during the second delivery to eliminate the pressure difference D_P between the first and second delivery.

Adaptive correction block 18, on the other hand, stores an electronic adaptive correction map containing an adaptive correction coefficient C_{AD} for each engine point defined by a respective pair of engine speed N and load L values.

More specifically, the electronic adaptive correction map is defined by a two-dimensional matrix, each box of which is identifiable by a respective pair of input parameters (engine speed N and load L), and contains a respective adaptive correction coefficient C_{AD} value.

In the example shown, the adaptive correction coefficient C_{AD} value indicates the correction to be made to duty cycle DC of control signal S_{COM} to take into account the deviation of the injection system and engine from nominal conditions, as a result, for example, of injection system and engine component part ageing or other factors.

With reference to Figure 3, electronic control unit 4 also comprises an update block 20, which receives pressure difference D_P, and supplies adaptive update coefficient C_{AG}, which is determined according to the equation:

$$C_{AG}=(D_P/K_P)*K_R$$

where K_P represents a pressure gain indicating the variation in fuel pressure in common rail 5 alongside a variation in duty cycle DC of control signal S_{COM}. For example, pressure gain K_P may indicate the variation in fuel pressure in common rail 5 alongside a predetermined variation in duty cycle DC, *e.g.*, one percent of duty cycle DC of control signal S_{COM}.

K_R is a numerical relaxation term of predetermined value. In the example shown, relaxation term K_R is so established as to allow electronic control unit 4 to complete correction of control signal S_{COM} in a predetermined number of engine cycles, while at the same time ensuring correct operation, even in the event of errors in determining pressure difference D_P or estimating the value of gain K_P. The value of relaxation term K_R may preferably, though not necessarily, range between 0.1 and 10^{-4}.

Adaptive update coefficient C_{AG} is used by adaptive correction block 18 to update the electronic adaptive correction map to take into account the deviation of injection system 2 and the engine from nominal conditions.

In the example shown, the adaptive correction coefficients C_{AD} stored in the electronic adaptive correction map are updated each time by electronic control unit 4 as a function of the updated adaptive update coefficient C_{AG} value and of the engine point, *i.e.*, engine speed N and load L.

More specifically, the adaptive correction coefficients C_{AD} stored in the electronic adaptive correction map are preferably, though not necessarily, updated when the engine is running steadily, *i.e.*, when, for example, engine speed N remains within a given range for a given time, and the temperature of the engine is above a given threshold.

For this purpose, the adaptive correction coefficients C_{AD} in the two-dimensional matrix are constantly updated as a function of the updated adaptive update coefficient C_{AG} by means of a known linear interpolation operation. For example, the adaptive correction coefficients C_{AD} may be updated each time over a number of boxes in the two-dimensional matrix, as a function of the engine point, *i.e.*, load L and speed N. In the example shown, the new value assigned to each said box may be determined by linearly weighting the adaptive update coefficient C_{AG} as a function of the proximity of the current engine point (L, N) with respect to the engine points of the boxes.

Operation of electronic control unit 4 will now be described, assuming high-pressure pump 6 effects a first and second fuel delivery to common rail 5 in the same engine cycle and in time with fuel injection into the first and second cylinder respectively.

In time with the first delivery and as a function of required pressure P_R and actual pressure P_E, control block 16 of electronic control unit 4 determines the duty cycle DC_1 of control signal S_{COM} to be supplied to pressure regulator 9 to bring the pressure in common rail 5 to the same value as required pressure P_R.

Once the first delivery is completed, high-pressure pump 6 effects the second delivery in time with injection into the second cylinder, and control block 16 corrects the duty cycle DC_1 of control signal S_{COM} to pressure regulator 9 as a function of total correction coefficient C_{CR}.

In the example shown, during the second delivery and as a function of the engine point (N, L), static correction block 17 and adaptive correction block 18 respectively supply static correction coefficient C_{CL} and adaptive correction coefficient C_{AD}, which are added in adding block 19, which in turn supplies total correction coefficient C_{CR} to correction block 16.

When the engine is running steadily, electronic control unit 4 also provides for updating the electronic adaptive correction map stored in adaptive correction block 18 and containing adaptive correction coefficients C_{AD}.

At this step, update block 20 acquires the pressure difference D_P between the first and second delivery made in the last engine cycle, and processes pressure difference D_P to determine the adaptive update coefficient C_{AG} to supply to adaptive correction block 18, which, as a function of the engine point (N, L), updates the boxes in the two-dimensional matrix of the electronic adaptive correction map.

As will be clear from the foregoing description, the above method also applies in the event high-pressure pump 6 performs more than two fuel deliveries to common rail 5 at each engine cycle.

In which case, during each delivery following the first, control block 16 corrects the duty cycle DC_1 of the control signal S_{COM} calculated for the first delivery, by means of a total correction coefficient C_{CR} calculated by a correction block 15 relative to the delivery in question.

The pressure control method may obviously be applied both to injection systems performing a number of fuel injections into the same cylinder at each engine cycle, and to injection systems performing, at each engine cycle, a sequence of individual injections into a number of respective cylinders.

The control method described has the advantage of ensuring the same fuel pressure in the common rail during each delivery made by the high-pressure pump at each engine cycle, thus improving the stability and reducing the consumption and emissions of the engine.

By constantly updating the adaptive correction coefficients C_{AD} in the adaptive correction map, the control method also has the big advantage of providing for extremely "vigorous" pressure control, *i.e.*, independent of variations in characteristic injection system and engine parameters, caused, for example, by ageing of injection system and/or engine component parts.

Clearly, changes may be made to the control method as described and illustrated herein without, however, departing from the scope of the present invention.